On the calculation of fuel savings through lightweight design in automotive life cycle assessments

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Abstract

Background, aim, and scope Lightweight design is a common means of reducing a passenger car's fuel consumption. In order to calculate the resulting fuel savings, one has to estimate the total energy that is needed to move a certain weight over a defined distance in a distinct way, and express this energy in liter of gasoline or diesel. This can be accomplished by the so-called fuel reduction value (FRV) and based on a standardized driving cycle, e.g., the New European Driving Cycle (NEDC). The aim of this paper is to explain the theoretical background of the calculation of fuel savings in automotive lightweight life cycle assessments (LCAs) of internal combustion engine (ICE) vehicles in greater detail than it has been done before, to describe the resulting factors and their different applications, and to point out some notable particularities that need to be taken into account when conducting this type of LCA study.

Materials and methods The first part of the paper explains the theoretical background of the FRV based on physical correlations and simulations. Based on these findings, its application in the context of automotive LCAs is described. The respective characteristics and preconditions are explained in detail.

Results It is shown that for LCAs that deal with automotive parts or assemblies, it is not permissible to multiply their respective net weight by the FRV under the assumption that

the vehicle's performance remains unchanged. However, the consideration of secondary lightweight effects concerning engine displacement or gear ratio is only possible under this assumption. This entails a significantly higher FRV, but in turn only allows for the calculation of the net fuel reduction, which is zero for the reference part and carries a negative sign for all lightweight design options. In practice, both FRV (0.12 and 0.28 l/(100 km*100 kg) for diesel vehicles resp. 0.15 and 0.35 l/(100 km*100 kg) for gasoline vehicles) are equally likely in case that no comprehensive information is available about whether a weight-induced power train adaptation will take place or not. This approach stresses the decision makers' responsibility to ensure such measures.

Discussion It appears to be indicated from a scientific point of view to include power train adaptations in automotive lightweight LCA studies in order to preserve functional equality in terms of the vehicle's driving performance. Yet, in practice this adaptation will most likely not take place if the weight difference is rather small. If there is no reliable information available that a weight-induced power train adaptation is guaranteed to take place, then a scenario without power train adaptation should be presented to the decision makers as well in form of an equally probable best and worst case.

Conclusions It has been shown that the fuel consumption in order to move a mass of 100 kg over 100 km can be obtained based on the NEDC driving cycle and the differential efficiency of gasoline and diesel engines. If possible secondary measures are taken into account (gear ratio and engine displacement) the resulting values can be augmented significantly. It has also been shown that it is advisable to utilize mass differences rather than mass ratios when calculating the lightweight effect on fuel consumption during the use stage. This implies that the resulting fuel

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saving of a lightweight component compared to the reference component carries a negative sign, while a lightweight vehicle's fuel consumption is positive.

Recommendations and perspectives It is strongly recommended to follow the proposed calculation procedure in future automotive lightweight studies. The authors further recommend the use of both FRV (with and without secondary measures) and the appropriate and explicit communication of the resulting implications.

Keywords Automotive · Design for environment · Eco-design · Fuel consumption · Fuel reduction value · Life cycle assessment · Lightweight design · Passenger car · Vehicle components

1 Background, aim, and scope

The Volkswagen Group has committed itself to the continuous environmental improvement of its products over the whole life cycle (Volkswagen AG 2008c). Life cycle assessment (LCA) has established itself as the predominant tool for evaluating the environmental progress from one product generation to the next (International Organization for Standardization 2006a, b; Schweimer and Levin 2000; Schweimer and Schuckert 1996; Volkswagen AG 2007a, b, 2008a, b, 2009a, b). It is known from past studies that about 85% of a passenger car's global warming potential is caused by the use stage, whereas about one third of an internal combustion engine (ICE) vehicle's total fuel consumption directly depend on its weight (Koffler 2007; Rohde-Brandenburger and Obernolte 2008). Accordingly, lightweight design has been recognized as one of the key measures for reducing vehicle fuel consumption, along with power train efficiency, aerodynamics and electrical power management.

At the same time, it is known that many lightweight materials such as aluminum, magnesium, or carbon fiber are comparatively energy-intensive to produce, and cause significantly higher CO_2 emissions prior to the use stage than, for instance, conventional steel concepts. This yields break-even kilometrages, i.e., the total driving distance required to compensate these emissions through reduced fuel consumption, that may render some lightweight designs unreasonable from an environmental point of view (Schallaböck et al. 2006). When dealing with lightweight design options, it is therefore essential to properly estimate the resulting fuel savings. This can be achieved by calculating the total energy that is needed to move a certain weight over a defined distance in a distinct way, and express it in liter of gasoline or diesel. The resulting fuel reduction value (FRV) is the crucial parameter in automotive lightweight LCAs and deserves special attention.

Publications on automotive lightweight LCAs are numerous (DaimlerChrysler 2007; Eberle 2000; Keoleian et al. 1998; Muñoz et al. 2006; Pflieger et al. 2005; Ribeiro et al. 2007; Saur et al. 1996; Schmidt et al. 2004; Subic and Schiavone 2006; Suzuki and Takahashi 2005). While some authors make use of the EUCAR Automotive LCA Guidelines as published by Ridge (1998) for use stage calculations, others assume a linear correlation between vehicle weight and fuel consumption. Yet, with the exception of (Eberle 2000), which is only available in German language, none of these publications describes the underlying physical correlations for the calculation of weight-induced fuel savings in detail. The aim of this paper therefore is

- to explore the theoretical background for the calculation of fuel savings in automotive lightweight LCAs in greater detail than it has been done before,
- to propose a simplified calculation procedure for weight-induced fuel savings,
- to describe the resulting factors and their different applications, and
- to point out some notable particularities that need to be taken into account when conducting this type of LCA study.

2 Theoretical background

2.1 Driving cycle

In order to quantify any vehicles fuel consumption, one has to specify the underlying driving cycle first. The driving cycle specifies speed and chosen gear as a function of time. In Europe, the New European Driving Cycle (NEDC) became a mandatory part of homologation testing for light-duty vehicles in 1996. It consists of 780 s in an urban cycle and 400 s in an extra-urban cycle. Its average speed is 33.6 km/h, the maximum speed 120 km/h, and the total distance is 11 km (Fig. 1). The underlying EU directives also specify requirements concerning ambient temperature, auxiliary units, etc. to ensure comparability of fuel consumption figures (European Economic Community 1970, 1980; European Union 2004).

While one may question the representativeness of the NEDC with respect to a passenger car's "real" fuel consumption, its fundamental advantage is that it provides a standardized and approved basis for calculation. As the NEDC is used to measure all published fuel consumption figures in Europe, it shall also serve as a reference for all further considerations in the context of automotive lightweight LCA. Needless to say, the general procedure would remain the same for other driving cycles.
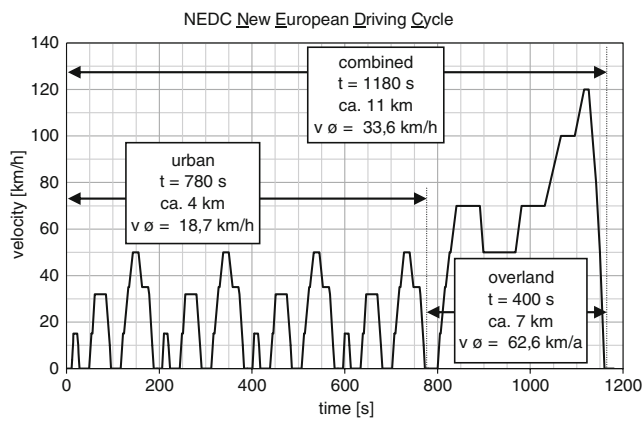
Fig. 1 Time and speed pattern of the New European Driving Cycle (*NEDC*)

2.2 Calculation of the mass-induced energy demand

Sections 2.2 to 2.4 are, in essence, a summary of (Rohde-Brandenburger and Obernolte 2002, 2008). Nevertheless, it is worthwhile to recapitulate them here as they will form the basis for all further considerations and have only been available in German so far.

Following the NEDC profile, a vehicle's power train has to provide the traction force to overcome three types of driving resistance:

$$\text{rolling resistance } F_R = m*g*f_R\,[N] \quad (1)$$

$$\text{aerodynamic resistance } F_L = (\rho/2)*v^2*c_W*A\,[N] \quad (2)$$

$$\text{acceleration resistance } F_a = m*a\,[N] \quad (3)$$

with

m	vehicle weight (kilogram)
g	gravitation constant (meter per second squared)
f_R	rolling resistance coefficient (dimensionless)
ρ	air density (kilogram per cubic meter)
v	velocity (meter per second)
c_W	air drag coefficient (dimensionless)
A	front surface (meter squared)

The mechanical work W [J] can then be obtained through their respective integration over the distance s (meter).

$$W = \int F*ds \quad (4)$$

Since the NEDC's velocity profile cannot be expressed through a simple mathematical function, the integral is calculated as the sum of all work increments in between $t=0$ and $t=1{,}180$ s.

$$
\begin{aligned}
W_R &= \sum \left(F_{R,i}*\Delta s_i\right) \\
&= \sum \left(m*g*f_R*\Delta s_i\right) = m*g*f_R*\sum \Delta s_i = m*g*f_R*C_{WR}
\end{aligned}
\quad (5)
$$

$$
\begin{aligned}
W_L &= \sum \left((\rho/2)*v_i^2*c_W*A*\Delta s_i\right) \\
&= (\rho/2)*c_W*A*\sum \left(v_i^2*\Delta s_i\right) \\
&= (\rho/2)*c_W*A*C_{WL}
\end{aligned}
\quad (6)
$$

$$
W_a = \sum \left(m*a_i*\Delta s_i\right) = m*\sum \left(a_i*\Delta s_i\right) = m*C_{Wa} \quad (7)
$$

The characteristic values C_{WR}, C_{WL}, and C_{Wa} are constants that are independent of the respective vehicle and specific to the driving cycle. The values for the NEDC can be taken from Table 1.

By using these constants, it is possible to calculate the total energy required for the NEDC profile in (J). Yet, W_L is negligible in order to calculate the energy needed to move a certain weight through the NEDC profile since it is independent of the vehicle's mass. Also, one has to take into account that the energy needed to overcome the acceleration resistance is stored as kinetic energy and is therefore partially recuperated during deceleration to overcome rolling and aerodynamic resistance. About 15% of the NEDC total distance of 11 km is deceleration phase. Because rolling resistance is virtually independent of the vehicle's velocity, the related work also decreases by 15%.

Using eqs. 5 and 7, one can calculate the total mass-induced energy demand for the NEDC as follows:

$$
\begin{aligned}
W_{sum} &= W_R*0.85 + W_a \\
&= m*(0.85*g*f_R*C_{WR} + C_{Wa})
\end{aligned}
\quad (8)
$$

For 100 km and 100 kg, the mass-induced energy demand therefore is

$$
\begin{aligned}
W_{sum(100\,kg,100\,km)} &= (100\,km/11\,km)*100\,kg* \\
&\quad (0.85*9.81\,m/s^2*0.01*11013\,m + 1227\,m^2/s^2) \\
&= 1.9503*E06\,J \approx 1.95\,MJ.
\end{aligned}
$$

The question remains, how much fuel is consumed by a gasoline or diesel engine in order to supply this energy.

2.3 Simplified fuel consumption calculation procedure

The degree of efficiency η of an ICE heavily depends on its point of operation concerning revolutions per minute (rpm)

Table 1 Characteristic values C_{WR}, C_{WL}, and C_{Wa} for different driving cycles

	NEDC (EU)	Combined fuel economy[a] (US)	10–15 mode (JP)
C_{WR} [m]	11,013	17,198	4,165
C_{WL} [m³/s²]	3,989,639	6,341,415	699,767
C_{Wa} [m²/s²]	1,227	2,221	687

[a] 55% city (FTP-75)/45% highway (HFET)

and engine output. In general, it can be characterized as follows:

$$\eta_{total} = P_{out,\,total}/P_{in,total} \qquad (9)$$

with

P_{in} energy input in liters fuel per hour (l/h)=(kW)
P_{out} engine output in kilowatts (kW)

The fuel consumption characteristics of an ICE can be depicted with the help of the Willans line method (Ross 1997).[1] These lines display the direct correlation between the energy intake and output for a certain rpm level, and can be derived from the measured values of an engine characteristic graph. Especially for low output and low rpm (<4,000 min⁻¹), which are typical of the NEDC, the Willans lines run almost parallel (Fig. 2). Their nearly constant slopes likewise represent a nearly constant *differential efficiency*, i.e., a running engine's efficiency whilst providing an additional amount of power output.

(Rohde-Brandenburger 1996) showed that the differential efficiency of engines with the same working process is, in contrast to their overall efficiency, very similar. The ascertained arithmetic mean for 4- and 6-cylinder naturally aspirated gasoline engines was 0,264 l/h/kW. Figure 2 shows the corresponding graph for a current 4-cylinder turbocharged gasoline engine. Again, the Willans lines run almost parallel, with an arithmetic mean of 0.273 l/h/kW. It appears to be reasonable to make use of the differential efficiency in order to estimate the extra fuel consumption caused by an additional power output. Based on work rather than on power, it calculates to

$$\eta_{diff,g} \approx 0.264 \text{ l}/(h*kW) = 0.264 \text{ l/kWh}$$
$$= 0.07\overline{3} \text{ l/MJ} \approx 42\% \qquad (10)$$

for naturally aspirated gasoline engines (with $\rho_{gasoline}$= 0.75 kg/l and H_u=43.5 MJ/kg), to

$$\eta_{diff,g} \approx 0.273 \text{ l}/(h*kW) = 0.273 \text{ l/kWh}$$
$$= 0.076 \text{ l/MJ} \approx 40\% \qquad (11)$$

for turbocharged gasoline engines (with $\rho_{gasoline}$=0.75 kg/ l and H_u=43.5 MJ/kg), and to

$$\eta_{diff,d} \approx 0.220 \text{ l}/(h*kW) = 0.220 \text{ l/kWh}$$
$$= 0.06\overline{1} \text{ l/MJ} \approx 46\% \qquad (12)$$

for turbocharged diesel engines (with ρ_{diesel}=0.84 kg/l and H_u=42.5 MJ/kg).

The insight that a running engine consumes the same amount of fuel for a given additional power output in the relevant area of its engine map constitutes a substantial simplification for the calculation of weight-induced fuel consumption.

2.4 Calculation of the weight-induced fuel consumption (NEDC)

Sections 2.2 and 2.3 provide virtually all data necessary to calculate the weight-induced fuel consumption. The total work of rolling and acceleration resistance for 100 kg and 100 km based on the NEDC amounts to 1,95 MJ (f_R=0,01). If we further assume that 2% of the engine's additional energy output is lost in the gearbox,[2] the mass-induced fuel consumption calculates to

$$V_{100\,kg,\,NEDC} = 1.95 \text{ MJ}*1.02*0.07\overline{3} \text{ l/MJ}$$
$$\approx 0.15 \text{ l}/(100 \text{ km}*100 \text{ kg}) \qquad (13)$$

for naturally aspirated gasoline engines, to

$$V_{100\,kg,\,NEDC} = 1.95 \text{ MJ}*1.02*0.076 \text{ l/MJ}$$
$$\approx 0.15 \text{ l}/(100 \text{ km}*100 \text{ kg}) \qquad (14)$$

for turbocharged gasoline engines, and to

$$V_{100kg,\,NEDC} = 1.95 \text{ MJ}*1.02*0.06\overline{1} \text{ l/MJ}$$
$$\approx 0.12 \text{ l}/(100 \text{ km}*100 \text{ kg}) \qquad (15)$$

for turbocharged diesel engines.

These values are again very close to the average data published by Ridge (1998). Now, if you multiply a vehicle's

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[1] named after Peter William Willans (1851–1892), inventor of the Willans high-speed steam engine

[2] estimate for manual and dual-clutch gearboxes such as the Volkswagen DSG®
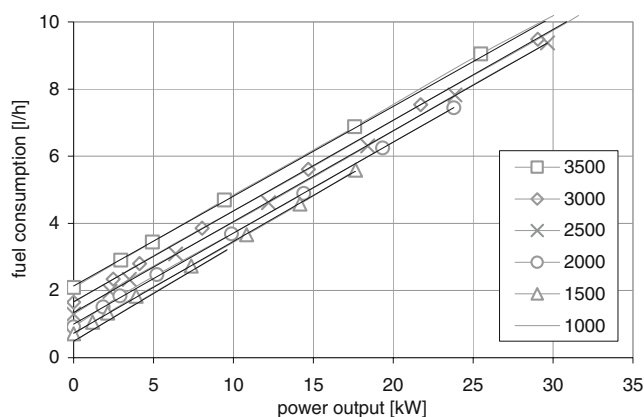
Fig. 2 *Willans lines* and resulting trendlines of a 1.4 l TSI gasoline engine (90 kW) for low output and low rpm

curb weight by the respective value for *V*, you get the *weight-induced share of its total fuel consumption*. For a current 2-door Golf VI with a 90 kW TSI engine and a curb weight of 1241 kg, this means that roughly 1.86 of its 6.0 l/100 km combined fuel consumption (NEDC) are weight-induced (~31%). Likewise, the displayed values can be used to calculate the *weight-induced fuel consumption of a given component* by multiplying them by the component's total mass. For instance, the weight-induced fuel consumption of a fender that weighs roughly 2.5 kg amounts to 3.75 ml of gasoline per 100 km.

So far, all calculations have been based on the assumption that no constructional adjustments are made to the engine or the gearbox. This is likely when the weight reduction is rather small. Yet, the larger the weight reduction, the more probable an adjustment of the gear ratio or the engine displacement becomes. This assumption is considered to be valid for mass-produced cars in general, since their driving performance's target values are set at the very beginning of the product development process and need not be exceeded. Hence, substantial weight reduction can be 'invested' in reducing fuel consumption instead.

These so-called secondary effects were simulated for different small, compact and mid-sized vehicles (Rohde-Brandenburger and Obernolte 2008). It was shown that they differ considerably depending on the vehicle's weight and size, its engine displacement, and whether an induction or turbo engine was applied.

Table 2 gives a comprehensive overview of all ascertained values. It is evident that the fuel reduction values with no further adaptation to the power train are much smaller. Again, the displayed values are consistent with the ranges published in the EUCAR Automotive LCA Guidelines (Ridge 1998).

3 Application to LCA

When applying the results obtained in section 2 to automotive life cycle assessment, one has to be aware of the underlying assumptions and the resulting constraints. This section will therefore discuss certain particularities related to the FRV, its application and the resulting values.

Functional unit The definition of the functional unit is one of the most important steps during goal and scope definition (Finkbeiner et al. 2006, International Organization for Standardization 2006a). In the realm of automotive lightweight LCA, the first and fundamental definition is whether one will assess a full vehicle or a single component,[3] e.g., the entire system or a subsystem. In both cases, it is desirable to preserve functional equality before and after the lightweight measure on the subsystem as well as on the system level (Cooper 2003). A weight reduction should therefore not result in improved vehicle driving performance, but can instead be employed to lower the vehicle's fuel consumption even further via secondary measures (extension of gear ratio, reduction of engine displacement). Hence, utilizing an FRV that already incorporates these measures appears to be indicated in order to preserve functional equality as much as possible. It has therefore become customary within the Volkswagen AG to deploy the respective arithmetic mean of the values displayed in the far right column of Table 1 by rule of thumb, i.e. 0.28 and 0.35 l/(100 km*100 kg) respectively (diesel/gasoline).

Calculation of the use stage First, the FRV shall be applied in automotive LCA studies where one or more lightweight design components are to be compared to the status quo (*component study*). In this case, the FRV does not express the components' *mass-induced fuel consumptions* as described in section 2.4, but *a decrease (or increase) in fuel consumption* as compared to a reference component (status quo). It is a widespread misapprehension that these two measures carry the same meaning.

The multiplication of the reference component's net weight by the FRV is generally not feasible if, for the sake of full functional equality, power train adaptations are to be taken into account (see above). This is because these adaptations do not apply to the reference component, but solely to the lightweight concepts. The corresponding FRV can therefore only be combined with weight differences.

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[3] The term "component" refers to single parts (e.g. a fender) as well as to assemblies (e.g., a seat).

Table 2 Ascertained fuel reduction values in (l/(100 km*100 kg)) (Rohde-Brandenburger and Obernolte 2008)

Engine type	No adaptation[a]	Adaptation[a]	Min	Max	Arithmetic mean
Gasoline	0.15	Gear ratio	0.29	0.39	0.32
		Displacement	0.36	0.45	0.39
Diesel	0.12	Gear ratio	0.27	0.30	0.29
		Displacement	0.24	0.29	0.26

[a] Power train adaptation to achieve equal driving performance, e. g., extension of gear ratio or reduction of engine displacement

Hence, the *decrease (or increase) in fuel consumption* for a given design option i calculates as:

$$\Delta C_{comp,i} = \Delta m_i * V_{100 \text{ kg, NEDC}} * 0.01$$
$$= (m_{comp,i} - m_{comp,ref}) * V_{100kg, \text{ NEDC}} * 0.01 \qquad (16)$$

with

$\Delta C_{comp,i}$ weight-induced decrease (or increase) in fuel consumption of component design option i (l/100 km)

$m_{comp,i}$ component mass of design option i (kilogram), and

$m_{comp,ref}$ reference component mass (kilogram).

This, in turn, entails that all lightweight design options in automotive lightweight LCAs cause negative fuel consumptions, i.e. *fuel savings*, while the reference component's fuel saving is zero. For example, if a vehicle's body structure weight would be lowered from 350 kg (status quo) to 250 kg, then the *fuel saving* of the reference component as currently produced equals zero, and that of the lightweight design option is $\Delta m_i * V_{100 \text{ kg, NEDC}} * 0.01 =$ $(250-350) * V_{100 \text{ kg, NEDC}} * 0.01 = -V_{100 \text{ kg, NEDC}} = -0.35$ l/ 100 km for a gasoline engine.

In contrast, if the functional unit would be the vehicle itself instead of a single component (*vehicle study*), then the fuel consumption of the reference vehicle would be known and that of the lightweight design vehicle would be:

$$C_{veh,i} = C_{veh,ref} + \Delta C_{veh,j} = C_{veh,ref} + \sum_{i=1}^{n} \Delta C_{comp,i} \qquad (17)$$

with

$C_{veh,i}$ fuel consumption of vehicle design option i (l/100 km)

$C_{veh,ref}$ fuel consumption of reference vehicle (l/100 km)

$\Delta C_{veh,j}$ weight-induced decrease (or increase) in fuel consumption of vehicle design option j (l/100 km)

$\Delta C_{comp,i}$ weight-induced decrease (or increase) in fuel consumption of component design option i (l/100 km), and

n   total number of all lightweight measures within vehicle design option j.

This strict differentiation between component and vehicle lightweight LCAs as well as the utilization of mass differences rather than mass ratios poses a refinement of the calculation methods published by Ridge (1998).

3.1 Communication of results

If a lightweight component's fuel consumption carries a negative sign, then so does the slope of the graphic representation of the resulting greenhouse gas emissions over the vehicle's running distance. Likewise, the production and the recycling stages need to be incorporated in the same chart in form of the respective differences between their net values and the ones of the reference part (Fig. 3).

Two kinds of important information can be derived from this chart: the before mentioned *break-even kilometrage* (see section 1) as well as the overall *net decrease of greenhouse gas emissions* due to the lightweight design measure. The one information that cannot be deduced is the relative fuel saving compared to the status quo in percent, as this would employ the division by zero. It can therefore not be calculated meaningfully for single components based on the underlying assumptions concerning functional equality and power train adaptation.

4 Discussion

As shown above, it appears to be indicated from a scientific point of view to include power train adaptations in
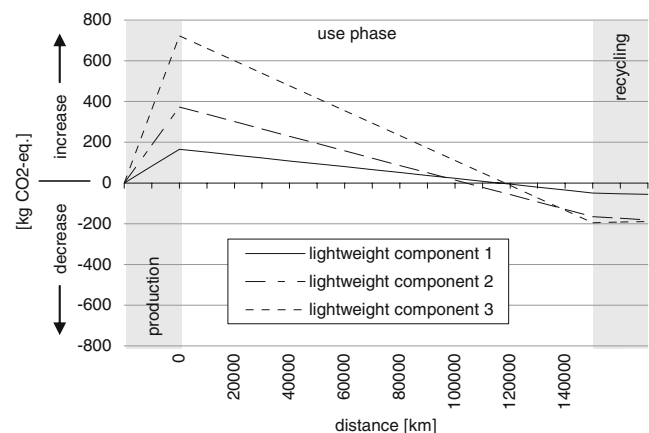

Fig. 3 Graphic representation of different lightweight components' greenhouse gas emissions

automotive lightweight LCA studies in order to preserve functional equality in terms of the vehicle's driving performance. Yet, in practice this adaptation will most likely not take place if the weight difference is rather small or if the lightweight design option is introduced rather late in the product development process. At the same time, it is very difficult to quantify for a single component how large its weight reduction needs to be to allow for a power train adaptation if other lightweight measures are likely to appear in the vehicle but not known comprehensively.

From a practitioner's point of view, it therefore appears to be necessary to make it very clear to the respective decision makers that the FRV is *the* crucial parameter within any automotive lightweight LCA. If there is no reliable information available that a weight-induced power train adaptation is guaranteed to take place, then a scenario without power train adaptation should be presented to the decision makers in form of an equally probable worst case. This approach emphasizes the decision makers' responsibility to ensure that these measures actually take place.

Some may also find it implausible (or at least unsatisfactory) that there is no relative fuel saving in percent in component studies. A possible solution to this problem would be to transform the component study into a vehicle study using formula 17 instead of formula 16 (with $n=1$). This, however, will result in only marginal relative fuel savings unless the weight reduction of the specific component is significant in comparison to the vehicle's total curb weight. Another supposable approach could be to define a "zero option" (no component at all) as reference. Apart from being highly unrealistic in most component studies, the zero option in the context of automotive lightweight LCA clearly denominates the status quo before lightweight measures are taken. For these reasons, this approach should also be excluded from consideration.

Another point of criticism that frequently arises is the fact that standardized driving cycles for homologation testing are not really representative in terms of people's 'real' driving behavior. Their average and top speeds are often supposed to be too low. It is often criticized that a more dynamic driving behavior would result in even higher FRVs as acceleration and deceleration phases become more frequent and/or more pronounced. This is all true and shall not be questioned. However, and this is often neglected, it is also true that a dynamic driving behavior will result in a fuel consumption increase on the vehicle level that will overcompensate any fuel reduction on the component level. Any other reasoning would be contradictory, as dynamic driving can never be better for the environment than moderate homologation cycles. In addition, for reasons of consistency and transparency with regard to customer communication, one should generally utilize the legally binding standardized driving cycles. For these reasons, the

utilization of comparatively high FRVs ($>>0.3/0.4$ l/(100 km*100 kg) (diesel/gasoline)) in component lightweight studies that is justified with 'dynamic' or 'real' driving behavior is a clear case of window-dressing.

As far as the empirical validity of the proposed factors is concerned, one should be able to reproduce them on a dynamic power analyzer, which is used to measure fuel consumption during homologation testing. For this approach to be viable, two conditions have to be met. First of all, the difference between the respective vehicle's curb weight before and after the weight reduction would have to exactly match the difference between the upper and lower bound of a given weight class (e.g., 110 kg, compare European Union (2004)). Secondly, the road resistance would have to be measured before and after the weight reduction via the respective coasting distances in order to calibrate the dynamic power analyzer properly. If these two conditions are met, one should be able to reproduce the theoretical FRVs of 0.12 and 0.15 l/(100 km*100 kg), respectively.

5 Conclusions

It has been shown that, based on the NEDC driving cycle and the differential efficiency of gasoline and diesel engines, the fuel consumption in order to move a mass of 100 kg over 100 km amounts to 0.12 l of diesel and to 0.15 l of gasoline respectively. Accordingly, if you decrease the vehicle's weight by 100 kg, the fuel consumption per 100 km is reduced by these values. If possible secondary measures are taken into account (gear ratio, engine displacement), these values can be augmented significantly.

It has also been shown that it is advisable to utilize mass differences rather than mass ratios when calculating the lightweight effect on fuel consumption during the use stage in order to properly display that the FRV represents fuel savings rather than absolute fuel consumptions (hence Fuel *Reduction* Value). In turn, it implies that the results of component studies differ from the results of vehicle studies concerning their signum. While the resulting fuel saving of a lightweight component carries a negative sign (in contrast to the reference component, whose fuel saving is zero), a lightweight vehicle's fuel consumption is positive just like the reference vehicle's known standard gasoline consumption.

6 Recommendations and perspectives

It is strongly recommended to follow the proposed calculation procedure in future automotive lightweight studies of ICE vehicles. Especially the question of

secondary measures is crucial to the outcome of automotive lightweight life cycle assessments and has to be addressed thoroughly. The authors therefore recommend the use of both FRV (with and without secondary measures) and the appropriate and explicit communication of the resulting implications.

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